HARDENED CONCRETE AND ITS PROPERTIES

Concrete that has partially gained its strength is called *hardened concrete*. When it comes to hardened concrete, it is generally understood that concrete is 28 days old and older. Hardened concrete properties are those that are effective throughout the life of the structure in which the concrete is used. These are properties such as strength, durability, deformation, permeability, volume stability, shrinkage and creep.

These properties, which gain importance according to the place where the concrete is used, depend on the composition of the concrete, its fresh properties, the processes applied during placing and compaction in the forms, the storage conditions in the form and the ambient conditions after the form is removed. These properties are tried to be determined by tests carried out on samples taken from the concrete when it is fresh.

Since such tests do not include effects other than the concrete composition, they do not give precise information about the concrete in the building. However, an idea about the quality of concrete in the building is obtained by using such test results. In cases where this is not sufficient, tests can be carried out directly on the concrete in the building or a decision can be made by examining the concrete samples to be taken from the building in the laboratory.

STRENGTH OF CONCRETE

The basic characteristic sought in hardened concrete is strength. Strength should not be considered as a necessary condition for a structure to stand alone. Because of the other properties of concrete with high strength are generally at the desired level. Therefore, except for very special cases, compressive strength is taken into account as a measure of concrete quality. While designing the concrete to be used in a building, the magnitude of the loads that the building will be exposed to is taken into account, and the concrete is designed and produced to carry these loads with a certain safety.

Here are some reasons why compressive strength is the most important characteristic sought in hardened concrete:

- Determining the compressive strength of concrete is much easier and simpler than determining its other characteristics.
- Concrete is mostly used to be subjected to compression.
- If the compressive strength is known, it is possible to get an idea about the magnitudes of other strength types.
- Compressive strength provides qualitative information about other properties of concrete. For example, a concrete with high compressive strength is considered to have low permeability and high performance.

Concrete is considered as a composite material consisting of cement paste and aggregate particles dispersed in this paste. In this respect, the strength of concrete is directly related to the strength of the cement paste, the strength of the aggregate and the adherence between the cement paste and the aggregate.

The compressive strength of concrete is determined on the specimens prepared in the size and shape specified in the standards. After the specimens are kept for the prescribed time under standard curing conditions, they are broken under axial compression and the compressive strength is calculated for the concrete in question.

Compressive strength is usually determined on 15 cm cubed or cylindrical specimens with a diameter of 15 cm and a height of 30 cm. In addition, 10 cm and 20 cm cube specimens and 10 cm diameter and 20 cm high cylindrical specimens are also used. The tensile strength is determined either on the specimens used in the compression test or on the prismatic specimens.

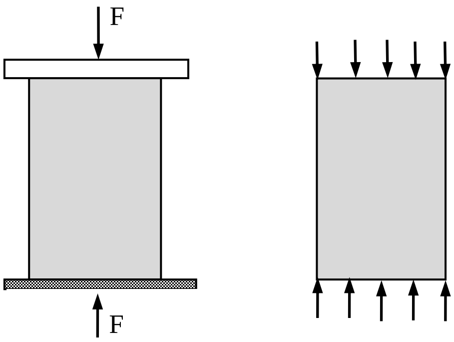
Fresh concrete is filled into sample molds as specified by the standards and stored in a humid room for 24 hours. At the end of this period, the specimens removed from their molds are kept in a room with 95% relative humidity at 20±2ºC, known as standard curing conditions, or in water at this temperature until the test date.

On the test day, the specimens are removed from the curing chamber and they are allowed to dry partially. The upper surfaces of the samples are relatively rough as they are smoothed with a trowel. This causes stress concentration in the compression test. In order to prevent this, the cube samples are laid on their side faces and broken in that way. Since this is not possible in cylindrical specimens, sometimes only the upper face is smoothed; sometimes both the upper face and the lower face are smoothed or made smooth by capping with a suitable material. One of the materials used for the cap is sulfur. The thickness of the cap should not be more than 5 mm.

The specimen molds can be steel, plastic or fiberglass. Fresh concrete is filled into cube molds in two layers and cylindrical molds in three layers, and each layer is tamped 25 times with a steel bar 16 mm in diameter and 60 cm in length. The compaction process should be completed by gently hitting the outside of the mold with a plastic mallet after tamping. The upper surface of the mold should be carefully smoothed by making a cutting action with a steel trowel or finishing trowel. Finally, the samples must be recorded by labeling.

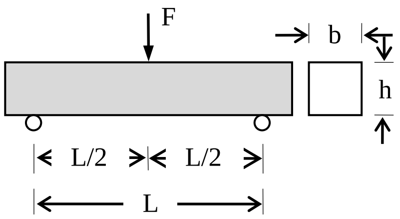
In the compression test, the specimen is broken by applying a force that increases with a certain speed. Today, a press that performs this process automatically is used. There are steel blocks above and below where the sample is placed in the press to apply force. The lower block is fixed and the upper block is a spherical shaped and movable head rested on a bed. The surfaces of the lower and upper blocks in contact with the specimen are hardened steel and are very smooth surfaces.

The tensile strength of concrete is considered to be in the order of $\frac{1}{8}$ to $\frac{1}{10}$ of its compressive strength. However, there are empirical relations in the literature to estimate the tensile strength of concrete depending on the compressive strength.



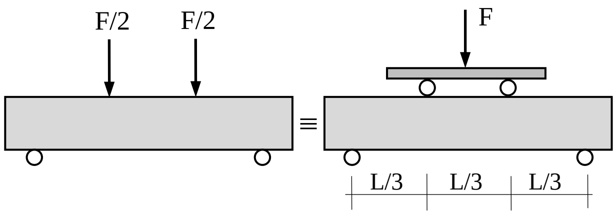
Here, F is the force causing the fracture; A is the cross-sectional area of the specimen. Accordingly, the compressive strength is calculated in the form of $\sigma_c = \dfrac{F}{A}$.

Although the tensile strength is determined by direct tensile test on prismatic specimens, it is determined indirectly by bending and/or splitting tests, since it is difficult to perform the direct tensile test. In the bending test, prismatic specimens in $10 \times 10 \times 40$ cm or other dimensions are turned on their side faces and placed on two supports. The specimens are then broken by loading them from the mid-point or at the ⅓ point of the span.



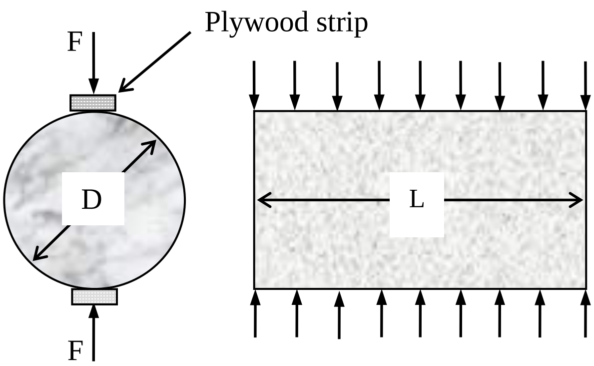
$$\sigma_t = \frac{3\ F \times L}{2\ b \times h^2} \text{ (Mid-point loading)}$$

Here, F is the force causing fracture and σ_t is the tensile strength at bending.



$$\sigma_t = \frac{F \times L}{b \times h^2} \text{ (One-third point loading)}$$

In the splitting test, standard cylindrical specimens are usually laid on their side faces and loaded along the directrix. Thus, the specimen is split by the effect of linear load acting along its directrix. In some cases, cube specimens are also used to determine the splitting tensile strength.



The splitting tensile strength (σ_t) is calculated as below:

$$\sigma_t = \frac{2\ F}{\pi\ L \times D}$$

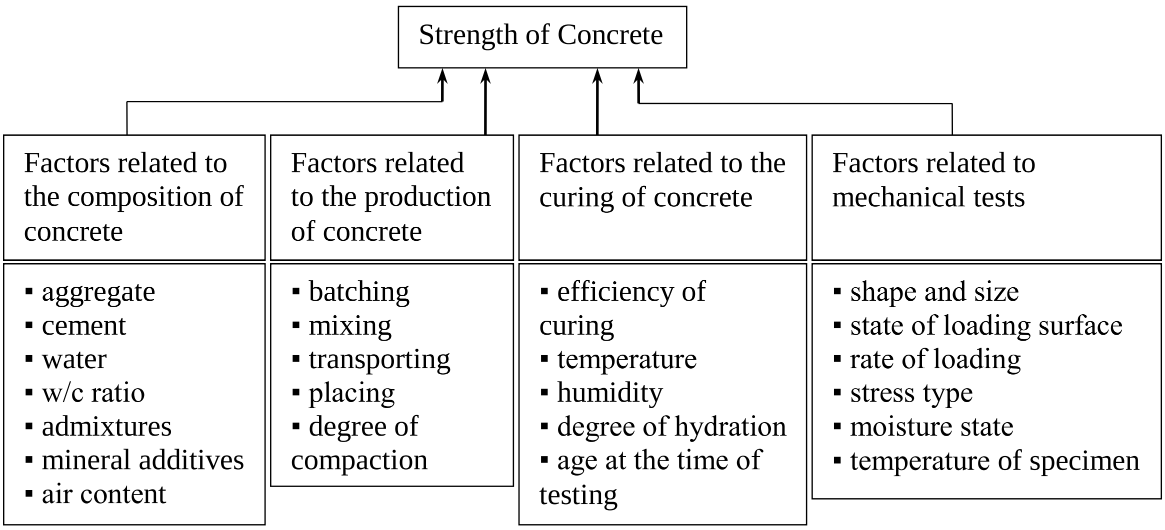
Here, F is the maximum line load, which leads to split. L is the length of the cylinder specimen and D is the diameter or the width of the cylinder specimen.

It is reported in the literature that the tensile strength in bending is 50% to 100% higher than the actual tensile strength, and the splitting tensile strength is 25% to 50% lower than the actual tensile strength.

FACTORS AFFECTING THE STRENGTH OF CONCRETE

The strength of aggregates used in concrete production is generally sufficient. For this reason, the importance of the strength of cement paste in terms of the strength of concrete is better understood. Adequate strength of cement paste not only increases the bearing capacity of concrete, but also contributes to stronger adherence between cement paste and aggregate particles.

The strength of concrete, which has many large voids in its structure, naturally decreases. In order to increase the strength of the cement paste, first of all, it is possible to reduce the voids other than the gel voids present in the cement paste as much as possible. These spaces are capillary spaces, entrapped air voids and entrained air voids formed by the air-entraining chemical admixtures within the cement paste. Therefore, the primary way to maximize strength is to minimize the voids in the concrete. For this, first of all, a good concrete mix design and adequate curing should be the priority steps. It should not be forgotten that another way to reduce the amount of voids in the concrete structure is to increase the hydration products. Good cure is essential for this. The factors affecting the strength of concrete can be summarized as follows:



Factors Related to the Composition of Concrete

Cracking of the concrete occurs either in the form of crushing of the cement paste or the fragmentation of the aggregate particles, or both, or the loss of adherence between the aggregate and the cement paste. Generally, since the strength of the aggregate is high, fracturing occurs mostly in the form of crushing of cement paste and loss of cement paste-aggregate adherence. For this reason, aggregate is not decisive in terms of strength loss in conventional concretes. Aggregate surface texture, shape and cleanliness are extremely important in terms of adherence. Rough, angular and clean aggregate grains provide better adherence with cement paste. However, it is difficult to place and compact the concrete produced with this type of aggregate. When placing and compaction is insufficient, the amount of space in the concrete increases and therefore the strength decreases.

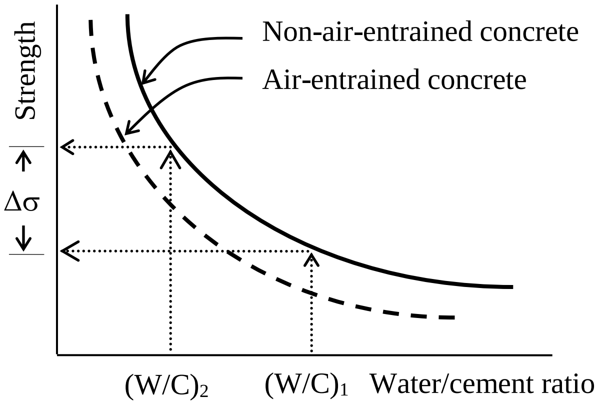
The maximum aggregate particle size and aggregate granulometry affect the workability and therefore the amount of water and cement added to the concrete mix. As the maximum aggregate size increases, the amount of water for a certain degree of workability decreases accordingly. However, there is no practical benefit to increasing the aggregate size beyond a certain limit. The granulometry of the aggregate also has an effect on strength through workability. Another important factor affecting the strength of concrete is the harmful substances in the aggregate and the mineralogical structure of the aggregate.

The most important factors affecting the strength of concrete are cement and water or the water to cement (W/C) ratio. The strength of the cement paste and its strong adherence to the aggregate particles make a significant contribution to the strength of the concrete. The amount of cement paste in the concrete mixture is proportional to the total surface area of the aggregate particles to be coated. In relation to this, the minimum amount of cement required in 1 m^3 of concrete, C_{min}, is given in relation to the maximum aggregate particle size (D) as follows:

$$C_{min} = \frac{550}{\sqrt[5]{D}} \quad [kg/m^3]$$

For conventional reinforced concrete, D≅20-30 mm is assumed and C_{min}=300 kg/m^3 is taken. As the amount of cement in the concrete mix increases, the strength of the concrete also increases. However, because of economy, shrinkage, creep and some other reasons, its composition is as important as the amount of cement. The amount of C_2S and C_3S components, which are effective in the development of cement paste strength, and the fineness and the amount of water in the cement paste are also effective on the strength of concrete. A water amount of 0.25 to 0.30 by weight of cement is sufficient for hydration.

When more water than required for hydration is used, the strength of the cement paste and accordingly the strength of the concrete decreases. However, water has another function, such as wetting the aggregate particles in the concrete mix and facilitating their movement in the paste, in short, making the concrete workable. Because of this function, the water/cement ratio rarely goes below 0.45. Otherwise, if the amount of water is reduced in such a way as to worsen the workability, this time the concrete cannot be placed and compacted well.



When the water/cement ratio decreases from $(W/C)_1$ to $(W/C)_2$, an increase of $\Delta\sigma$ occurs in the strength.

Since the structure of concrete that cannot be compacted enough will be porous, its strength decreases. To overcome this, plasticizers are used. By using these admixtures, the water to cement ratio can be reduced without a decrease in the workability of the concrete. Therefore, it is possible to increase the strength of concrete in this way.

There are several empirical relations that mathematically express the relationship between the strength of concrete at any age and the water to cement ratio of concrete cured under appropriate temperature and humidity conditions. The most widely known of these are:

<u>Bolomey`s relation</u>:

$$f_c = k_B \times \left(\frac{C}{W} - 0.50 \right)$$

Here, f_c is the compressive strength of concrete, in N/mm^2, $10 < k_B < 30$ N/mm^2 (for 28-day concretes).

<u>Graf`s relation</u>:

$$f_c = \frac{f_{cc}}{k_G} \times \left(\frac{C}{W} \right)^2$$

Here, f_c is the strength of concrete, in N/mm^2, f_{cc} is the 28-day standard compressive strength of cement, f_{cc}=42.5 N/mm^2 (for CEM I 42.5), $4 < k_G < 10$ (independent of concrete age).

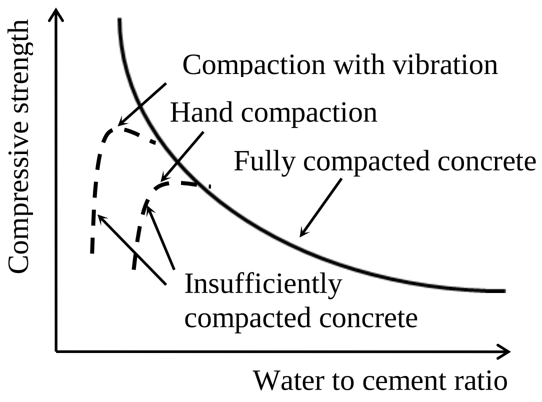
<u>Feret`s relation</u>:

$$f_c = k_F \times \left(\frac{V_c}{V_c + V_w + a} \right)^2$$

Here, f_c is the strength of concrete, in N/mm^2, $90 < k_F < 280$ N/mm^2 (for the 28-day concrete), V_c, V_w, and a are the amounts of cement, water and entrapped air in absolute volume, respectively.

Factors Related to the Production of Concrete

Even though its composition is well adjusted, if a concrete is not mixed well, carefully placed in the form and not fully compacted, there will be a decrease in its strength. Insufficient mixing or prolonged mixing may result in the formation of a non-uniform mixture. Prolonged mixing may not only cause the aggregates to crumble, but also may cause an increase in concrete temperature, resulting in increased water requirement for desired workability. Appropriate methods should be applied to prevent segregation and bleeding during transportation and placement. A vibrator should be used when compacting to eliminate large voids that cause serious strength loss. Excessive vibration may cause segregation in concrete.



The relation between compressive strength and W/C ratio of concrete

Sometimes, despite all the care, placing and compacting the concrete in the form is not perfect. Concrete may segregate and/or bleed. The reason for this is that concrete is not suitable for that job in terms of composition and consistency. For this reason, it is necessary to constantly consider the place of use and the conditions of the construction site while determining the concrete composition.

It is difficult to fully compact a concrete with a very low water to cement ratio and large voids may remain in the concrete. Therefore, as indicated by the dashed lines in the figure above, concretes with very low water/cement ratio show a significant decrease in strength.

Factors Related to the Curing of Concrete

Strength of concrete depends on hydration of cement; hydration depends on ambient humidity, temperature and curing time. Storing the concrete under suitable conditions for hydration is called “curing”. The standard curing is to keep the concrete in water at 20±2^{o}C (Relative humidity of 95% and above) for 28 days. These conditions can be easily achieved in the laboratory. It is accepted that the concrete reaches 65-80% of the strength it will gain after 28 days of standard curing, after 7 days of standard curing. If hydration develops slowly, the keeping time of the concrete in the form is extended. On the other hand, form removal time can be shortened if hydration is accelerated by various methods.

In any case, the water in the concrete composition is sufficient for the hydration of the cement. If the evaporation of this water is prevented, the necessary humidity condition for hydration is provided. For this reason, it is necessary to keep the concrete wet for a few days, starting 1-2 hours after pouring. For this, either the surface of the concrete is wetted or the concrete surface is covered with wet burlap or nylon to prevent water loss of the concrete. It is very important to keep not only the humidity but also the concrete temperature within certain values in the first days after pouring. A large amount of water loss at high temperature can cause hydration to cease.

The rate of the chemical reaction between cement and water varies depending on the temperature of the environment and the concrete. This reaction is slow at low temperatures and fast at high temperatures. For this reason, it is necessary to keep the concrete at the most suitable temperature and humidity in order to protect it at both high and low temperatures and to reach its normal strength. It should not be forgotten that a hot and windy environment has an accelerating effect on evaporation and water loss due to evaporation occurs faster in thin-section elements compared to thick-section elements.

The optimum temperature for pouring concrete is around 15-16^{o}C. When the temperature of the concrete is higher than 30^{o}C, the final strength of the concrete will be lower than desired. Temperatures below 10^{o}C cause a decrease in the hydration rate. At 0^{o}C or lower, the hydration of cement greatly slows down.

As the temperature of the concrete increases, hydration accelerates. The acceleration of hydration reactions is reflected in the strength development of concrete. One of the methods used to shorten the holding time of the concrete in the form is to heat the concrete in the forms. Concretes whose strength development is accelerated by heat treatment show a slight decrease in final strength compared to control concrete. Hydration of cement stops completely at temperatures below -10^{o}C. However, in practice, hydration is considered to stop on days when the air temperature drops below +5ºC. These days are not counted for the molding period.

Although the strength development of concrete progresses over time, it is normally accepted that it gains the target strength in three weeks. Accordingly, the form removal time varies between 3 days and 3 weeks, depending on whether the molded elements are loaded or not.

After placing, compacting and smoothing the concrete surface, the concrete should be subjected to moist curing in order to provide the water necessary for the hydration of the cement. There are several methods for moist curing. These can be divided into two categories:

Water curing: With this method, additional moisture is provided to the concrete and the loss of moisture from the concrete is prevented. Water curing is usually accomplished by spraying or sprinkling water on the concrete or using wet coatings such as cloth and sawdust.

Curing with covers: Using this method, moisture loss from the concrete is prevented. Curing by covering is accomplished by covering the concrete surface with a waterproof paper or plastic sheet, or by using some chemical admixtures.

Factors Related to Mechanical Tests

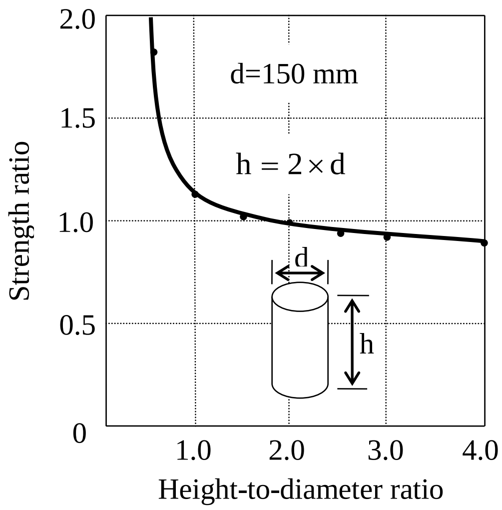
Whether the concrete used in a building is of the desired quality is determined by testing the specimens taken while pouring the concrete in the building after curing in the laboratory under standard curing conditions. The conditions for placing the concrete in the form, compacting and curing are different from the preparation and laboratory storage conditions of these specimens. For this reason, the strength of the specimens is not equal to the strength of the concrete in the building. However, the high strength of the specimens increases the probability of the high strength of the concrete in the building.

In addition, the fact that the strengths of the specimens are close to each other is an indication that the concrete in the building is homogeneous and that enough care is taken in the concrete-related processes. The experimentally determined strength on the specimens varies depending on the following factors. These factors are known collectively as the experimental conditions.

- The shape and size of the specimen,
- The moisture condition of the specimen,
- The loading surface condition of the specimen,
- The loading speed of the specimen,
- The temperature of the specimen.

The shapes of standard specimens are cube, cylinder and square prism. The shape is usually defined by the height/diameter ratio. This ratio, called *slenderness*, is 1 in cube specimens, 2 in standard cylindrical specimens, and greater than 4 in prisms. In specimens where the slenderness is greater than 2, the compressive strength is not affected by this ratio. As the slenderness goes below 2, the strength increases. There is also a difference between the compressive strength of the specimens with the same shape but different sizes. As a general rule, the smaller the specimen, the greater the compressive strength.

Due to the shape effect, the compressive strengths of standard cylinders and cubes are not the same. There is a mathematical relationship of $\sigma_{\text{silinder}} \cong 0.85 \times \sigma_{\text{küp}}$ between the standard cube compressive strength and the standard cylinder compressive strength made of the same concrete. The change in strength ratio depending on the height to diameter ratio is given below schematically.



Effect of change in height to diameter ratio on compressive strength of concrete

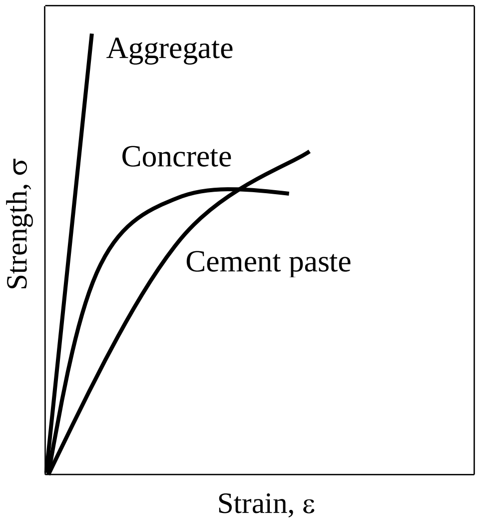
The compressive strength of wet concrete is lower than that of fully dry concrete, and its split tensile strength is higher than that of fully dry concrete. The bending tensile strength of fully dry concrete is also higher than that of wet concrete. However, when a wet concrete is left to dry, tensile stresses occur on the outside of the concrete since drying starts from the outside. The bending tensile strength of a concrete under this condition may be lower than both its fully dry strength and its wet strength. The correction factors suggested by the relevant standard for concrete cylinder samples that are not at standard height are given in the table below:

Height-to-diameter ratio	2.00	1.75	1.50	1.25	1.10	1.00	0.75	0.50
Multiplying factor	1.00	0.98	0.96	0.94	0.90	0.85	0.73	0.60

The rate of increase of the force applied to the concrete in the test is effective on the strength of the concrete. The faster the force is applied, the more the concrete breaks under the influence of a relatively high force. The effect of loading speed also depends on the strength level of the concrete. High-strength concretes are more affected by the loading speed than low-strength concretes. For standard tests, a constant loading rate of 1.5 to 3.5 kgf/cm^2 per second is applied until the specimen breaks according to the relevant standards.

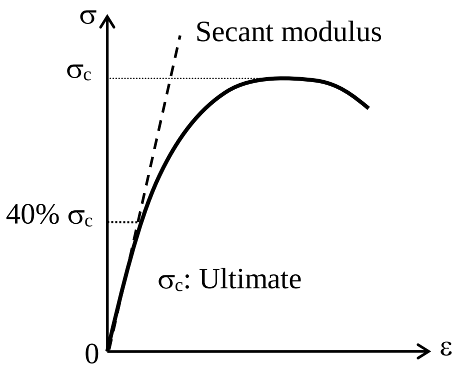
BEHAVIOR OF CONCRETE UNDER COMPRESSION

In conventional concrete, the effect of aggregate on strength is negligible, but its presence is important in terms of its effect on the behavior of concrete. The (σ-ε) curves of aggregate, cement paste and concrete under compression are given in the figure below. As can be seen from the figure, aggregate and cement paste show elastic behavior while concrete shows inelastic behavior. The resulting strain does not change linearly with the applied stress, and when the force is removed, the entire strain does not return.



Typical stress-strain curves for aggregate, cement paste, and concrete

It is possible to evaluate the deformation of concrete in two stages as short-term and long-term. Long-term behavior is time dependent and is known as *creep*. Here, the short-term behavior of concrete under load will be evaluated. The stress-strain diagram of the behavior of concrete in a short-term compression test is given below.



The diagram is usually in the form of a half parabola. Although there is no linear region of the diagram, it shows a nearly linear behavior at the beginning. Therefore, concrete is generally considered to be linear elastic in the stress region up to 40% of its ultimate strength.

Such an admission is made to facilitate calculations. However, the value to be taken for the modulus of elasticity in calculations is controversial. Because there is no definite linear part of the diagram, different elastic moduli are defined. For example, tangent modulus, secant modulus, dynamic modulus of elasticity.

The tangent modulus is valid for a very narrow region. The dynamic elastic modulus has the same drawback as it is usually a tangential modulus. Therefore, it is more realistic to take the secant modulus as the modulus of elasticity, since it represents the behavior of concrete in a wider region. Various empirical relationships have been developed between the elastic modulus of concrete and its compressive strength. Some of these are as follows.

$E = A(\sigma)^{1/n}$ Here σ is the compressive strength of concrete, A and n are constants.

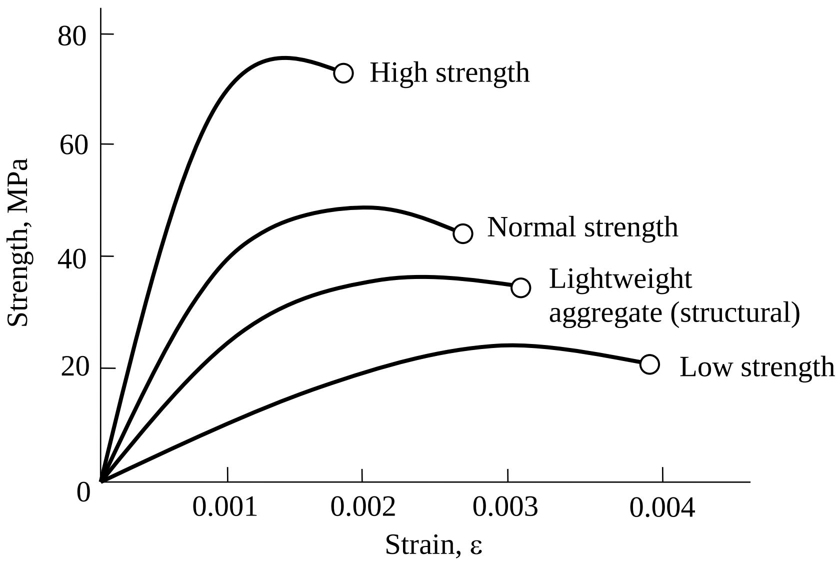
The relationship suggested by the American Concrete Institute is as follows:

$E = 4.73\sigma^{1/2}$ Here E is in GPa and σ in MPa.

The elastic modulus of concrete takes values between 100 000 and 400 000 kgf/cm^2, depending on the concrete class. The relation given by TS 500 in this sense is as follows.

$E = 10270 \times \sqrt{f_c} + 140\,000$ Here E is the modulus of elasticity, in kgf/cm^2, f_c is the characteristic cylinder compressive strength of concrete.

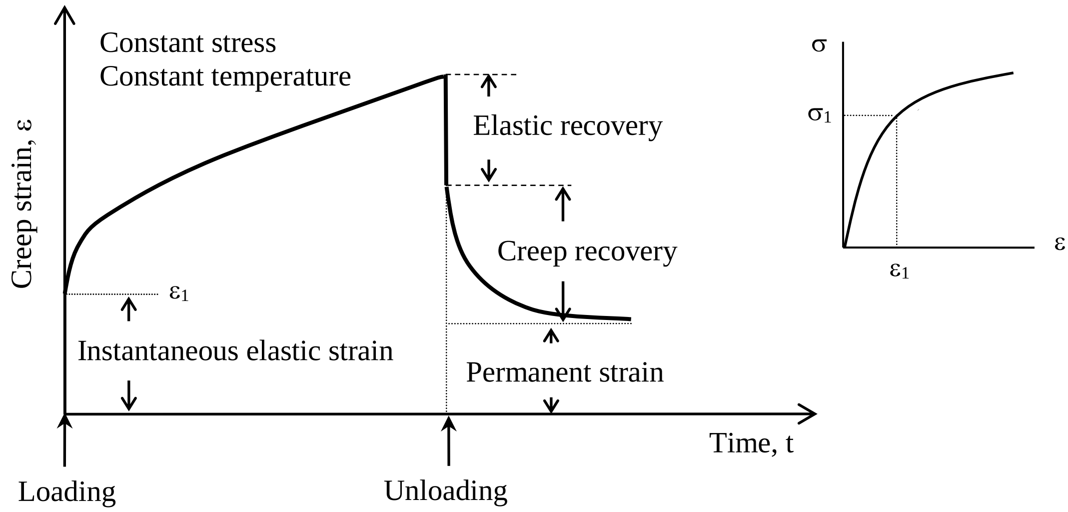
The shape of the stress-strain curve depends on the size of the microcracks in the concrete and is mainly a function of the compatibility between aggregate and cement paste. When they have similar strength and modulus of elasticity (porous lightweight aggregates in a normal-strength cement paste or normal aggregates in a high-strength cement paste), their stress-strain curves naturally tend towards linear as seen in the graph below. Because the stress concentration between the two occurs at a low level.



The nonlinearity of the shape of the stress-strain curve for normal aggregates increases with the decrease in the strength of the cement paste. Factors that increase aggregate-cement paste adherence increase the linearity of the stress-strain curve because adherence prevents the formation of cracks more effectively. The angular shape of the aggregate and its rough textured surface can be given among the factors that are effective here.

CREEP IN CONCRETE

Concrete structural elements are exposed to constant external forces or loads as well as live loads. Concrete structural element undergoes a sudden deformation under the effect of this constant load or force. In addition to this *instantaneous elastic deformation*, the concrete structural element also makes a time dependent deformation known as *creep*. The related representation is given below as the (σ-ε) diagram.



When the force applied to the concrete structural element is removed, it makes a sudden deformation equal to the deformation made when the force is applied to the concrete structural element. Concrete usually does not return to its original dimensions. For example, the majority of loads acting on reinforced concrete structures, such as the concrete's own weight, are long-term. For this reason, not only the sudden deformation of the concrete under these loads, but also the long-term deformation should be taken into account in the calculations.

SHRINKAGE IN CONCRETE

Concrete expands when it absorbs water and contracts when it dries. The volume change made by the concrete in this way is called *shrinkage*. Volume change due to water loss can occur in both fresh concrete and hardened concrete. The volume change that occurs in fresh concrete due to water loss is called *plastic shrinkage*, and the one that occurs in hardened concrete is called *drying shrinkage*. The shrinkage that occurs as a result of the reaction of hydrated cement with carbon dioxide in the atmosphere is known as *carbonation shrinkage*. This shrinkage is a special case of drying shrinkage. *Autogenous shrinkage* or *hydration shrinkage* occurs as a result of self-drying of the concrete during hydration, independent of environmental effects. This is a special case of drying shrinkage.

<u>Plastic shrinkage</u>: It is the shrinkage that occurs as a result of the aggregate particles settling at the bottom of the formwork while the concrete is in its plastic state and the evaporation of the water collected on the concrete surface. It occurs especially in elements with large surfaces such as floor and slab concretes. Concrete can crack easily as shrinkage

occurs before the concrete has hardened yet. Cracks seen on the concrete surface are generally cracks that occur as a result of plastic shrinkage. This type of shrinkage can be prevented by preventing water loss. Since the concrete is still plastic, wetting can be done by spraying, the concrete surface can be covered with wet burlap or plastic covers, or surface hardening chemicals can be sprayed on the concrete surface. The most common method is to keep the concrete surface constantly wet.

Plastic shrinkage can also be controlled by using wind breakers, reducing the concrete temperature, and accelerating the setting of the concrete. These precautions are only to prevent plastic shrinkage and resulting cracking. After the concrete loses its plasticity and hardens, this type of shrinkage does not occur and the concrete becomes more resistant to the stresses caused by shrinkage.

<u>Drying shrinkage</u>: Drying shrinkage occurs in the form of distortion or warping in the structural elements as a result of water loss from the hardened concrete. Concrete structural elements do not return to their original dimensions even if they are wetted afterwards. It is stated that the drying shrinkage is completed in one year under normal conditions.

<u>Hydration shrinkage</u>: It occurs as a result of the continuous reduction of water in the cement paste during hydration. If the water that decreases due to hydration cannot be supplied externally, the pressure balance between and on the surface of the gel particles that make up the cement gel is disrupted and shrinkage occurs as a result. This is especially common in the interior parts of mass concretes that have little contact with the outside and concretes with a low water to cement ratio. This shrinkage in the form of self-drying concrete is also known as *autogenous shrinkage*. Hydration shrinkage can last for months, usually stopping after a period of three months.

Both creep and shrinkage are time-dependent strains and result from the same internal process involving the movement of water. In the shrinking state, the driving force for water movement is environmental conditions that cause diffusion of water outward (i.e. water is lost). In the case of creep, the driving force is stress, which causes water to move from place to place in the concrete (i.e. no water loss). Thus, creep deformations occur in saturated concrete that is prevented from drying out. This is known as *basic creep*.

Creep strain depends on the direction of stress; however, moisture loss (free shrinkage) on drying involves equal contractions in all directions. In practice, we are generally concerned with the time-dependent deformation of concrete in the axial loading direction under the action of compression. In practice, creep and shrinkage occur simultaneously when concrete is exposed to its natural drying environment under load. It is important to know what is meant by "creep deformation". Many engineers measure all time-dependent deformations of concrete under load, without distinguishing between creep and drying shrinkage.

In the structure, an increase in axial deformation over time due to creep and shrinkage (e.g. column under compression), an increase in deflection (e.g. beam under bending action) or stress relaxation (e.g. a pre-stressed structural member; concrete contracts due to shrinkage and creep and pre-stressing) decreases over time). A time-dependent shrinkage can cause cracking if a concrete component is constrained and tensile stresses build up as it tries to contract. An important feature of creep and shrinkage is the fact that the strains do not fully return when the load is removed and the concrete is resaturated.

FACTORS AFFECTING CREEP AND SHRINKAGE

The main factors affecting creep and shrinkage and their direction of action are given below:

Composition of concrete: As a general rule, creep and shrinkage increase as the amount of cement and water increases, the water/cement ratio increases, and the aggregate/cement ratio decreases.

Strength of concrete: When force is applied, the higher the strength of the concrete and the greater the cement hydration, the lower the creep and shrinkage of the concrete.

The magnitude of the applied stress: The applied stress cannot naturally be greater than the strength of the concrete. However, the closer it is to the strength of the concrete, the higher the creep will be.

Environmental conditions: Moisture in concrete is very important in terms of creep. Environmental conditions such as temperature and wind increase evaporation and thus creep and shrinkage.

Dimensions of concrete member: In general, the creep decreases as the dimensions of the concrete member increase. As the surface area of the concrete member exposed to the atmosphere increases, evaporation accelerates; hence the shrinkage increases.

Similarly, as the ratio of surface area to volume of the member increases, the rate of shrinkage increases. Therefore, the shrinkage rate of small-volume members is greater than the shrinkage rate of large-volume members. However, the final shrinkage is roughly equal to each other.

The amount of reinforcement in the concrete member: As it does not shrink, reinforcement like aggregate prevents shrinkage of cement paste and reduces the shrinkage of concrete. However, if the concrete has not gained enough strength, the concrete may crack due to the internal stresses that occur due to friction between the reinforcement and the concrete.

Cracking due to shrinkage is frequently seen especially in slabs resting on the ground and road concrete. In order to intensify or prevent these cracks at certain points, the slabs are poured in blocks of certain sizes and joints are left between the blocks. These blocks, called ano, can vary in size from 2.5 to 9 m, depending on the slab thickness, the consistency of the concrete, and the maximum aggregate particle size.

DURABILITY OF CONCRETE

The durability of concrete is defined as the property of not losing its properties over time due to internal and external effects as long as it serves. Concrete in a structure should not only have the strength to withstand various types of loads, but also maintain its original shape and quality in any environmental conditions it serves over the years. In this respect, durability in hardened concrete is at least as important as strength.

In order to protect concrete from harmful environmental effects, it is a priority to produce quality concrete. However, due to the economy, manufacturers often have to compromise on quality. The quality of concrete is at risk due to both internal and external effects. Concrete may be exposed to external effects such as frost effect, atmospheric effects, harmful water effects, abrasion and impact effects, as well as internal effects such as thermal expansion, efflorescence, shrinkage, humidity and water absorption.

The most common durability problems can be listed as resistance to freeze-thaw, resistance to chemical effects, sulfate effect, resistance to abrasion, alkali-silica reaction, carbonation, resistance to volume changes.

<u>Freeze-thaw resistance</u>: Cement paste is very sensitive to freezing and thawing cycles as there are many small pores in it. When the temperature drops below 0^{o}C, the water starts to freeze at about -5^{o}C. The smaller the pore, the lower the temperature must be for ice formation to begin. Once the ice crystals are formed, the resulting 9% increase in volume causes pressure to build up in the pores by compressing the water remaining in the pores.

In terms of resistance to freeze-thaw, compactness is an important parameter. For this reason, it is necessary to produce a void-free concrete as much as possible. Because as the compactness increases, the freeze-thaw resistance increases. In this sense, air-entraining agents also increase the freeze-thaw resistance.

<u>Resistance to chemical effects</u>: Concrete is a material that can deteriorate under the influence of various chemicals and even pure water. However, in practice, the effects of acids and sulfates are mostly mentioned. Chemical durability of concretes can be achieved by producing a concrete with high compactness and low permeability, or by increasing the amount of cement, using cement with pozzolanic additives, and covering the concrete surface with an impermeable layer.

<u>Sulfate attack</u>: Sulfate attack occurs when sulfate ions penetrate the concrete from the external environment (groundwater or seawater). As a result of sulfate attack, the surface of the concrete acquires a whitish appearance and damage usually begins at the edges and corners of the concrete member, and then the concrete cracks and crumbles. The reason for this appearance due to sulfate attack is due to calcium sulfate (gypsum) and calcium sulfoaluminate (ettringite). Both products occupy a larger volume than the compounds they replace. Thus, the process results in the expansion and cracking of the hardened concrete.

<u>Abrasion resistance</u>: Streams, wind or traffic can abrade the concrete. If the surface abrasion caused by these effects on the concrete has started, it becomes difficult to prevent the progression of the destruction. For this reason, concrete that is open to such effects should be made strong at the beginning. It should take some precautions specially to ensure that its surfaces are hard. The use of hard aggregate may be a remedy.

Alkali-silica reaction: It negatively affects the durability as a result of causing the concrete to disintegrate and crumble. The alkali-silica reaction is a chemical reaction that occurs between the reactive silica in the aggregate and the alkalis (Na_2O, K_2O) in the cement. Since the gel formed as a result of the reaction is an expansion product, it may cause cracking of the concrete over time. The reaction is very slow and its effect may occur years later.

To prevent such reactions, it is necessary to use either aggregate that does not contain reactive silica or cement with low alkali content. It is stated that this reaction will not occur theoretically if the cement has an equivalent alkali content ($Na_2O+0.65K_2O \leq 0.60$). Another useful solution is to add pozzolan to the concrete. Because pozzolans contain very fine reactive silica, they react very quickly with the alkali in the cement. Thus, harmful expansion is prevented as the alkali-silica gel diffuses in the matrix.

Carbonation: There is some amount of carbon dioxide in the atmosphere. Rainwater and snow water take some CO_2 from the atmosphere and a weak carbonic acid is formed. Groundwater may also contain some dissolved carbon dioxide. When the concrete is exposed to the atmosphere or when groundwater containing CO_2 seeps into the concrete, a reaction takes place between CO_2 and $Ca(OH)_2$ that leads to the formation of $CaCO_3$.

Carbonation is a slow process. It usually starts on the surface of the concrete and progresses into the interior. Since $Ca(OH)_2$ decreases in the near-surface part due to carbonation, the alkalinity of the concrete in these carbonated parts decreases. This carbonation causes the steel reinforcement to become vulnerable to corrosion.

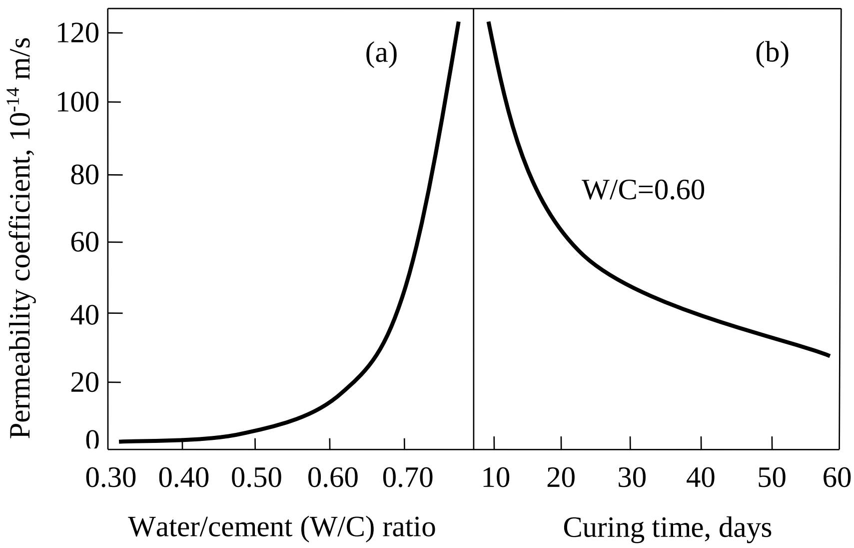
Resistance to volume changes: If there is a large amount of CaO, MgO in the cement composition, there may be an increase in volume in the concrete as a result of the reaction of these with water in the late period. However, this problem can be eliminated by controlling the composition of the cement very strictly during production. Therefore, when volume change is mentioned, thermal expansion and shrinkage that occur as a result of heat and humidity change should be understood. Concrete may crack if such volume changes are prevented. As the cracks reduce the resistance of the concrete against frost and chemical effects, the concrete may eventually crack and crumble.

Resistance to volume changes can be increased by choosing the appropriate material, adjusting the concrete composition, leaving joints at appropriate intervals for thermal expansion and shrinkage, and well-curing the concrete.

PERMEABILITY OF CONCRETE

The key to durability is “permeability”. In this respect, any remedial effort to reduce permeability is directly reflected in durability. Effects such as humidity and efflouresce depend on the permeability and water absorption of the concrete. Concrete with low permeability and low water absorption is also resistant to frost and chemical effects. The high density of concrete reduces permeability and capillarity. Permeability is a very important feature especially for water structures such as dams, water tanks, pools, irrigation channels.

Permeability can be reduced by choosing the appropriate material, adjusting the concrete composition, increasing the dosage, using mineral additives, and reducing the water to cement ratio. The use of placing and compaction methods that prevent concrete from segregation is also an important factor for impermeability. The effect of water to cement ratio and curing time on the permeability of concrete is shown graphically below.



Variation of permeability depending on water to cement ratio (a) and curing time (b)